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RESEARCH MEMORANDUM

DESIGN FACTORS FOR 4- BY 8-INCH RAM-JET COMBUSTOR

By Donald W. Male and Adolph J. Cervenka

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Cleveland, Ohio

NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

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SUMMARY

An investigation was made of a series of flame holders designed with the objective of providing a high combustion efficiency in a 4- by 8-inch ram-jet combustor 24 inches long at an inlet-air velocity of 200 feet per second, inlet-air pressure of 60 inches of mercury absolute, inlet-air temperature of 200° F, and near stoichiometric fuel-air ratio.

The most efficient and stable combustor designs investigated employed fuel injection directly at the upstream end of a flame holder that combined surfaces heated to incandescence by immersion in flame with a continuous path of low stream velocity for flame propagation between the upstream and downstream ends of the flame holder. Silicon-coated molybdenum was satisfactorily used as flame-holder material at the high temperatures encountered.

INTRODUCTION

One phase of NACA research on ram-jet combustion is the study of design principles for ram-jet combustors. A ram-jet combustor generally consists of a fuel injector followed by a fuel-air mixing length, a flame holder, and sufficient space for complete combustion.

An investigation was conducted from June 1947 to January 1949 at the NACA Lewis laboratory to study combustor design factors leading to a sufficiently high heat release and low internal drag to power a high-thrust, low-drag ram-jet engine. Two design principles investigated were the use of flame holders that employed incandescent surfaces heated by immersion in flame, as suggested in reference 1, and the elimination of the separate fuel-air mixing length by injecting the fuel directly at the upstream end of the flame holder. In this manner, combustion can exist at the point of fuel injection, allowing more efficient use of the available combustion space, and intermittent combustion in the mixing zone, a common cause of combustion instability is eliminated.

The experimental procedure involved determining combustion stability and efficiency and isothermal pressure drop for several combustors with various flame holders and fuel injectors at a simulated flight condition. At the simulated flight condition, the combustor inlet-air conditions were: inlet-air pressure, 60 inches of mercury absolute; inlet-air temperature, 200° F; inlet-air velocity, 200 feet per second; and fuel-air ratio, 0.05.

In addition to the design problem there exists the problem of materials for flame holders, because the temperatures attained are above the melting point of readily available alloys. The use of silicon-coated molybdenum was suggested by Roger Long of the Fabrication Division, Lewis laboratory, who also assisted in the procurement of it for use in this investigation.

APPARATUS

A rectangular combustor, which is adaptable to wing installations, was chosen for the investigation. A diagram of the 4- by 8-inch test installation is shown in figure 1. The combustor consisted of a constant cross-section, rectangular Inconel duct, 4 by 8 inches in cross section and 24 inches long, with an ignitor, a flame holder, and a fuel injector. The combustor and exhaust ducting were water-jacketed in order to prevent overheating and to permit measurement of heat losses. A water spray was installed at the downstream end of the combustor to cool the exhaust gases to temperatures that could be measured with thermocouples.

A Lucite window in the ducting, as shown in figure 1, permitted observation of a part of the combustor and a quartz window permitted visual verification of the absence of flame downstream of the water spray.

Inlet diffuser. - Air flows and pressures were controlled by means of variable-area inlet-diffuser and exhaust-nozzle sections and by remotely operated butterfly valves. A needle-type variable-area inlet diffuser was used during investigation of the first 11 flame holders (fig. 1). This diffuser was 18 inches long with a 4-inch-diameter circular cross section at its inlet and a 4- by 8-inch rectangular section at its outlet. The inlet-to-outlet area ratio was varied by moving axially a conical center body or "needle."

In order to have a direct view into the combustor and to take high-speed motion photographs of the combustion process, the needle-type inlet diffuser was replaced in later runs by a movable-wall diffuser. This movable-wall diffuser was rectangular in

cross section and was fabricated in two parts. The upstream part of the diffuser consisted of two movable walls mounted between two parallel fixed walls 8 inches long, 4 inches wide, and 2 inches apart. The two movable walls were hinged 4 inches apart at the
1145 downstream end and were remotely powered to move symmetrically. The downstream part of the diffuser had a fixed transition section 18 inches long diffusing from a 2- by 4-inch area to a 4- by 8-inch area.

A typical velocity profile at the exit of the movable-wall diffuser was lopsided. The profile was made symmetrical by the addition of a thin plate in the center of the diffuser, as indicated in figure 1. With both diffusers the velocity profiles indicated that the exit velocity was low in the center and high near the sides.

Exhaust nozzle. - A two-dimensional variable-area exhaust nozzle was used in the investigation of flame holders 1 to 9. The area was controlled by axial movement of a wedge into the throat section.

Fuel injectors. - Two types of fuel injector (fig. 2) were used. The first type consisted of tubes running across the duct parallel to the axis of the flame-holder components. Each tube had two rows of seven orifices for injection of the fuel and was designed to give a fuel-pressure drop of about 10 pounds per square inch at the lower fuel rates used in the investigations. This fuel injector, in a position directly upstream of the flame holder, was used in all the investigation unless otherwise stated.

The second type of fuel injector consisted of nine 30-gallon-per-hour, 80° hollow-cone, pressure-atomizing spray nozzles (rated at 100 lb/sq in. pressure differential) arranged to spray the fuel in the downstream direction. With both types of fuel injector, the fuel-injection ports were located at the upstream end of the flame holder and injected fuel in the downstream direction directly in line with the flame-holding bodies.

Fuels. - The fuels used in the investigation were liquid gasoline, specification AN-F-48b, liquid isopentane, and gaseous isopentane.

Ignitor. - An ignitor consisting of a high voltage electrode and a small fuel line shielded by a small cone with the spark arcing between the electrode and the tip of the fuel line was used for starting. The ignitor spark and ignitor fuel were always turned off during the runs.

Flame holders. - The various flame-holder designs investigated are discussed in the Results and Discussion. 1145

INSTRUMENTATION

Static pressures were measured by mercury manometers at stations 1 and 2 (fig. 1). Total temperatures were measured at station 1 by two iron-constantan thermocouples and at station 3 by nine chromel-alumel thermocouples located at the approximate centers of equal areas.

Water-flow rates in the quenching spray and cooling jackets and fuel-flow rates were measured by rotameters. Air-flow rates were metered with a variable, calibrated, slit-type orifice in the 12-inch inlet-air line. The air was heated to the desired inlet-air temperatures by electric heaters.

An automatic pressure recorder was used to determine the regularity and the magnitude of pressure pulsations during combustion with a few of the more efficient combustor designs. High-speed motion pictures (2400 frames/sec) were taken of combustion with one flame holder to affirm the absence of cyclic combustion.

PROCEDURE

The procedure followed in the development of the flame holders was largely experimental rather than theoretical. Often more than one change in the fuel type or state, fuel injector, flame holder, or other equipment were made simultaneously in an effort to arrive at a satisfactory type of combustor in as short a time as possible.

It was possible to obtain data at only one operating condition for some flame holders because of the limited life of Inconel, the best readily obtainable metal for high temperature use. In order to make comparisons of the efficiency of different flame holders, an attempt was made to investigate all flame holders at a standard set of inlet-air conditions. The conditions selected were as follows:

Inlet-air average velocity, ft/sec	200
Inlet-air static pressure, in./Hg absolute	60
Inlet-air temperature, °F	200
Fuel-air ratio	0.05

Unless otherwise stated, combustion efficiency was determined at these conditions.

Because no simple method has been found for directly measuring exhaust-gas temperatures in excess of 3000° F, combustion efficiency was determined by means of the heat-balance method. In this method, sufficient water is introduced through the water spray to reduce the exhaust-gas temperatures to a value that can be directly measured with thermocouples. The temperature was maintained between 500° and 700° F. In this temperature range, it was assumed that all the water had been vaporized and the combustion process arrested. Combustion efficiency is the ratio of actual enthalpy rise of the exhaust products, cooling water, and steam to the heating value of the fuel.

Combustion limits were determined in the following manner: Inlet-air pressure, temperature, and velocity were set at the desired values; fuel-air ratio was set at a value where combustion was stable and then was either increased or decreased until combustion ceased.

RESULTS AND DISCUSSION

Preliminary experiments. - Preliminary investigation of several different flame holders, both the single-stage gutter type and the multiple-stage type with gutters immersed in the combustion zone, gave similar results. Combustion was unstable at inlet-air velocities higher than 60 feet per second; and at fuel-air ratios richer than 0.025 combustion could not be stabilized at velocities greater than 40 feet per second. It was concluded that the source of combustion instability was not in the combustor but rather in the auxiliary ducting. The inlet-air duct comprised 500 feet of 12-inch pipe between the piston compressor supply and the test installation and this pipe might give rise to low-frequency pulsations.

To improve the stability, a variable-area diffuser was installed upstream of the combustor so that sonic flow could be maintained at all times in the diffuser. The effect was pronounced. A flame holder that could not be operated above the limits mentioned in the foregoing paragraph before installation of this diffuser could thereafter be operated up to inlet-air velocities of 140 feet per second at fuel-air ratios from 0.02 to 0.07. This flame holder consisted of two rows of four gutters each, as suggested by reference 1. All succeeding runs were conducted using a variable-area diffuser upstream of the combustor.

A similar effect was sought with the exhaust nozzle by running 1145
a flame holder both with and without choking at the nozzle, but no pronounced effect could be detected. Inasmuch as these runs were conducted with air flow choked at the diffuser inlet, it is probable that air-flow pulsations were minimized at this point; therefore any possible effect of exhaust-nozzle choking was minimized. The early part of the investigation showed that stability was much improved by the use of gutters immersed in the flame, as also shown in reference 1.

Two parallel rows of gutters. - Flame holder 1 (fig. 3) consisted of two rows of gutters spaced with their centers 5 inches apart and with 11 gutters in each row. The gutters, made of 1/8-inch Inconel, were 4 inches long, 1 inch from tip to base, 3/4-inch wide, and were mounted $1\frac{1}{2}$ inches between tips. Combustion limits are given in figure 4. Combustion was stable for inlet-air velocities up to 325 feet per second with liquid AN-F-48b fuel at a fuel-air ratio of 0.07. At a velocity of 200 feet per second combustion was stable at fuel-air ratios as lean as 0.018. Combustion efficiency was below 30 percent at the standard operating condition.

The stability of this flame holder was adequate for application at the specified flight conditions, but combustion efficiency was very unsatisfactory. In order to determine whether any of the dimensions of this flame holder can markedly affect combustion efficiency, several flame holders were made that involved various systematic changes from flame holder 1, which was taken as a standard. These flame holders were investigated with liquid AN-F-48b fuel.

Flame holder 2 contained 7 gutters in each row with the spacing between gutters increased to $2\frac{1}{2}$ inches to maintain the same combustor length. Flame holder 3 contained 15 gutters in each row with the spacing between gutters reduced to again give the same combustor length. Flame holder 4 contained 11 gutters in each row but had the rows closer together (4 in. between center lines of rows). Flame holder 5 contained 11 gutters in each row but had the gutter width increased to 1 inch. With all these flame holders the combustion limits were below those of flame holder 1, as shown in figure 4. Combustion efficiency was below 30 percent, indicating that combustion efficiency was not affected to a marked degree by changes in those dimensions that were varied in this series of flame holders.

Three rows of gutters. - A third row of gutters, similar to the two in flame holder 1, was placed in the middle of that design to compose flame holder 6. This flame holder was investigated with both vaporized isopentane and liquid AN-F-48b fuel and was found to have an efficiency of 50 percent with each fuel at an inlet-air pressure of 55 inches of mercury absolute. Combustion limits were below those of flame holder 1, as shown in figure 4. An indication of combustion efficiency was the condition of the flame holder at the end of approximately 10 minutes of operation. The deterioration of flame holder 6 (fig. 5) showed that higher combustion efficiency had been obtained with this design than with previous designs, which remained intact.

Staggered gutters. - Alternate gutters were staggered 1/4 inch from the row center line in each of the two rows of 11 gutters in flame holder 7 (fig. 6). The results of runs with this flame holder using liquid AN-F-48b fuel showed that the combustion efficiency was higher than that of any previously mentioned two-row design. Figure 7 is a photograph of flame holder 7 after 10 minutes of operation. The deterioration of the Inconel gutters gave evidence of temperatures in excess of 2600° F.

These results indicated that it was beneficial to have a continuous path of low stream velocity from the downstream end, which is the hottest and the best source of continuous ignition, to the upstream end, which is cooled the most by incoming air. This low-velocity path allows the flame to propagate as far upstream as possible toward the point of fuel injection. Any externally induced pressure fluctuation, which might cause flame blow-out at the upstream end, would have no lasting effect, because this continuous flame path would reestablish burning immediately. The incandescent downstream portions of the flame holder would provide immediate reignition, should a pressure pulse cause the entire flame to blow out.

The staggering of the gutters in flame holder 7 provided a continuous flow path by sheltering alternate edges of the gutters by the ones immediately upstream.

Simultaneous use of three rows and staggered gutters. - The improved results obtained separately by the addition of the third row of gutters and the staggering of the gutters indicated the design of flame holder 8, which consisted of three rows of staggered gutters (fig. 8). Alternate gutters were staggered 3/32 inch from the row center line in each of the three rows of 11 gutters. Investigation of this flame holder with vaporized isopentane injected at the upstream end of the flame holder yielded 65-percent combustion efficiency at an inlet temperature of 280° F. The flame holder deteriorated slightly during this run.

A second run was made with the isopentane fuel vapor injected 6 inches upstream, but the recorded data were invalidated because of failure of the water spray, which was required for the heat-balance method of determining combustion efficiency. The flame holder was severely deteriorated; only the three end gutters of the original 33 remained intact (fig. 9).

Other configurations. - In an attempt to develop a flame holder with an improved continuous flame path, two designs incorporating baffles instead of gutters were evolved. Flame holder 9 consisted of three rows of staggered plates, 30 plates in each row, with a slit between each plate (fig. 10). These slits permit continuous flame propagation between all regions of low velocity.

A model was constructed of Inconel. This model was investigated with vaporized isopentane injected at the upstream end of the flame holder. The plates glowed intensely and rapidly melted and broke away. The life of the plates in the downstream portion of the combustor was about 1/2 minute and was insufficient to permit data to be taken. Subsequent data taken after approximately the 4 minutes of operation required to set and stabilize conditions showed that combustion efficiency was 57 percent at an inlet-air temperature of 240° F and an inlet-air pressure of 56 inches of mercury absolute. The ratio of the total-pressure loss through the combustor to the inlet dynamic pressure was 3. Figure 11 shows the condition of flame holder 9 immediately after data were obtained. This figure also shows the position of the fuel injector. Inasmuch as the flame holders melted rapidly before data could be recorded, higher combustion efficiencies probably existed at the start of the run than were indicated by the data.

Flame holder 10 consisted of three corrugated Inconel strips with three 1/2-inch holes in each plane of corrugation (fig. 12), which are designed to serve the same function as the slits in flame holder 9.

Investigation of flame holder 10 was made with vaporized isopentane injected 6 inches upstream of the flame holder. Choking at the exit and failure of the exhaust-nozzle mechanism limited the inlet-air velocity to 150 feet per second. Subsequent runs were made without a variable-area exhaust nozzle. At an inlet-air velocity of 150 feet per second and an inlet temperature of

290° F, combustion efficiency was 80 percent. These data were taken near the end of 5 minutes of operation. The condition of this flame holder after 5 minutes running time is shown in figure 13. The ratio of the total-pressure loss through the combustor to the inlet dynamic pressure was 2.

Use of molybdenum. - The flame-holder designs that gave improved combustion efficiencies reached temperatures high enough to rapidly melt Inconel, thus preventing accurate determination of combustor performance. In an attempt to find a more heat-resistant material, one of the downstream gutters of flame holder 7 was replaced by a silicon-coated molybdenum prism to compose flame holder 11. In addition, the two rows of gutters were made to converge on each other slightly in order to utilize more of the central air stream for combustion (fig. 14). Figure 15 shows the molybdenum prism intact amid the remains of several melted Inconel gutters at the end of the 5-minute run. At an inlet-air pressure of 55 inches of mercury absolute and with the use of liquid AN-F-48b fuel, the combustion efficiency was 45 percent.

In order to substantiate further the applicability of silicon-coated molybdenum to flame-holder components, flame holder 12 was fabricated with the same dimensions as flame holder 11 except that the last five gutters in each row were replaced by silicon-coated molybdenum prisms. The flame holder was operated for 47 minutes at the standard operating conditions with only slight oxidation of the molybdenum in local spots where the coating apparently failed (fig. 16). The fuel used with this flame holder was liquid AN-F-48b.

Flame holder 13 duplicated flame holder 9 except that silicon-coated molybdenum plates were used instead of Inconel plates (fig. 7). Only 1/8-inch Inconel was available for the large retaining shell required to hold the plates. The shell rapidly melted during the investigation although the plates showed no deterioration. In this run, liquid isopentane was sprayed through the hollow-cone spray-nozzle fuel injector. Figure 18 shows the condition of the flame holder after 5 minutes of operation. The rough surface on some of the molybdenum plates is Inconel that melted and deposited there during operation. At the standard operating condition, combustion efficiency was 65 percent. The ratio of the total-pressure loss through the combustor to the inlet dynamic pressure was 3.

Magnitude of pressure fluctuations. - Pressure fluctuations in the combustor were recorded during the investigation of flame holder 13 and were compared to fluctuations recorded during isothermal flow (fig. 19). Combustor pressure varied less than

2 percent from the mean pressure. In addition, motion pictures were taken of the combustion process at 2400 frames per second during the investigation of flame holder 13. No indication of combustor pulsations could be observed from study of these photographs. These results verified audible observations that combustor pulsations were absent or negligible in flame holders combining surfaces heated to incandescence by flame immersion with a continuous low stream velocity flame path and fuel injection at the flame holder.

SUMMARY OF RESULTS

From an investigation of the design factors of a 4- by 8-inch ram-jet combustor, 24 inches in length, the following results were obtained:

1. Combustion was stable up to an inlet-air velocity of 325 feet per second with flame holder having flame-immersed, incandescent surfaces.

2. A continuous flame path of low stream velocity from the downstream portion of a flame holder to the upstream portion improved combustion efficiency.

3. Silicon-coated molybdenum used as flame holder components immersed in the ram-jet combustion zone had a service life greater than 47 minutes; under similar conditions Inconel lasted less than 5 minutes.

4. Combustion pulsations were absent or negligible in flame holders employing a continuous flame path and fuel injection at the flame holder.

5. Duct-pulsation effects were eliminated by maintaining sonic flow in a variable-area inlet to the test unit.

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National Advisory Committee for Aeronautics,
Cleveland, Ohio.

REFERENCE

1. Breitwieser, Roland: Performance of a Ram-Jet-Type Combustor with Flame Holders Immersed in the Combustion Zone. NACA RM E8F21, 1948.

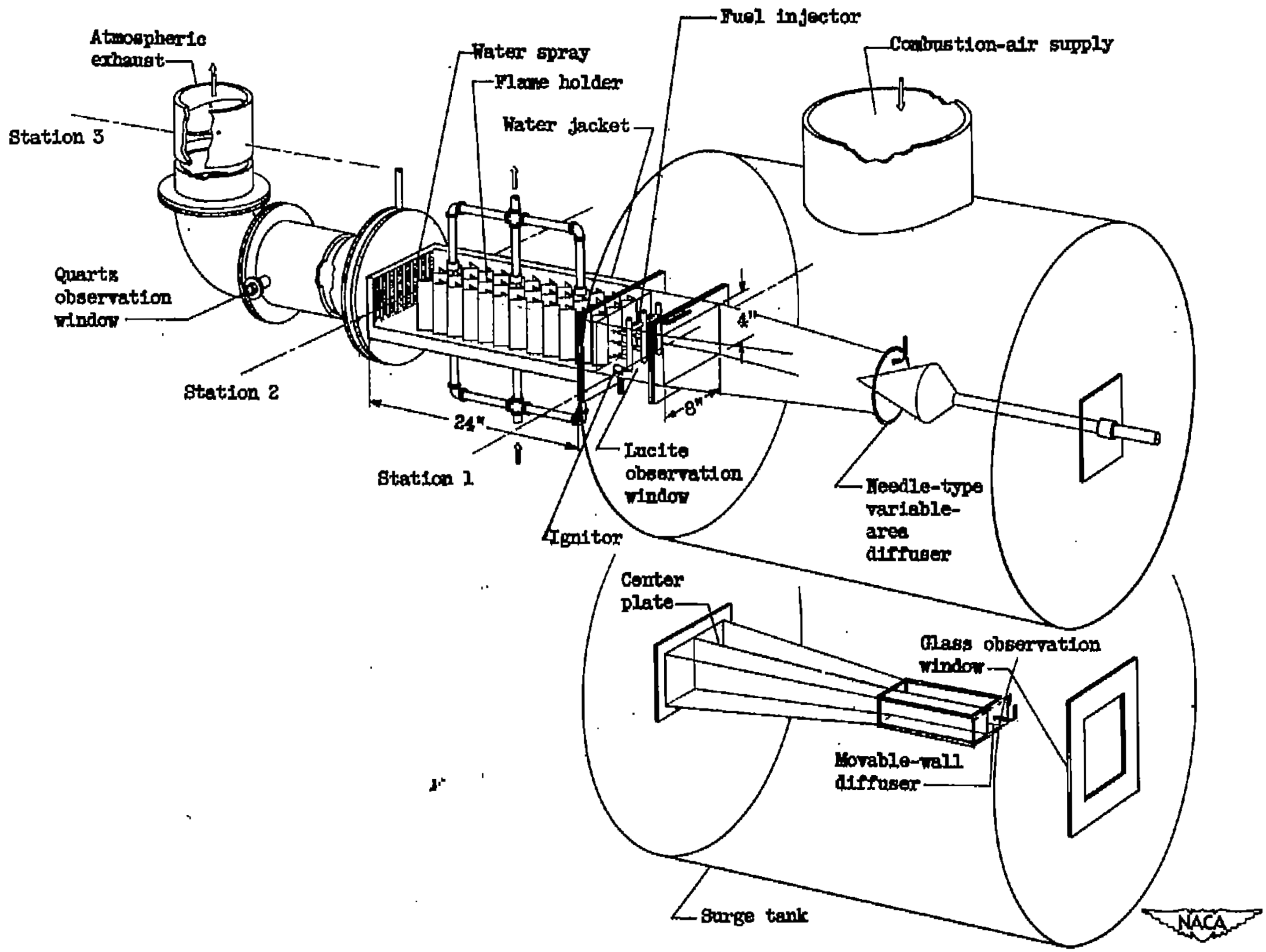

Figure 1. - Experimental setup of 4- by 8-inch combustor and auxiliary ducting.

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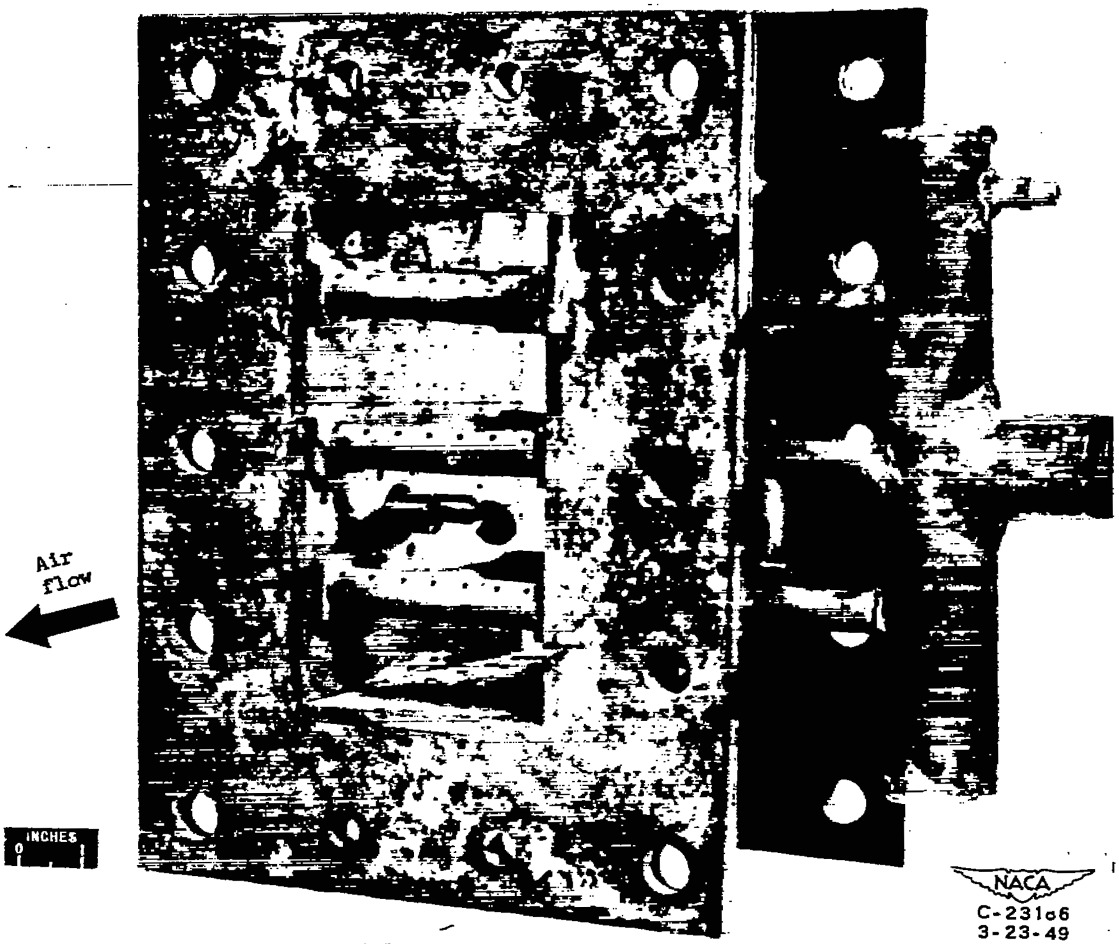
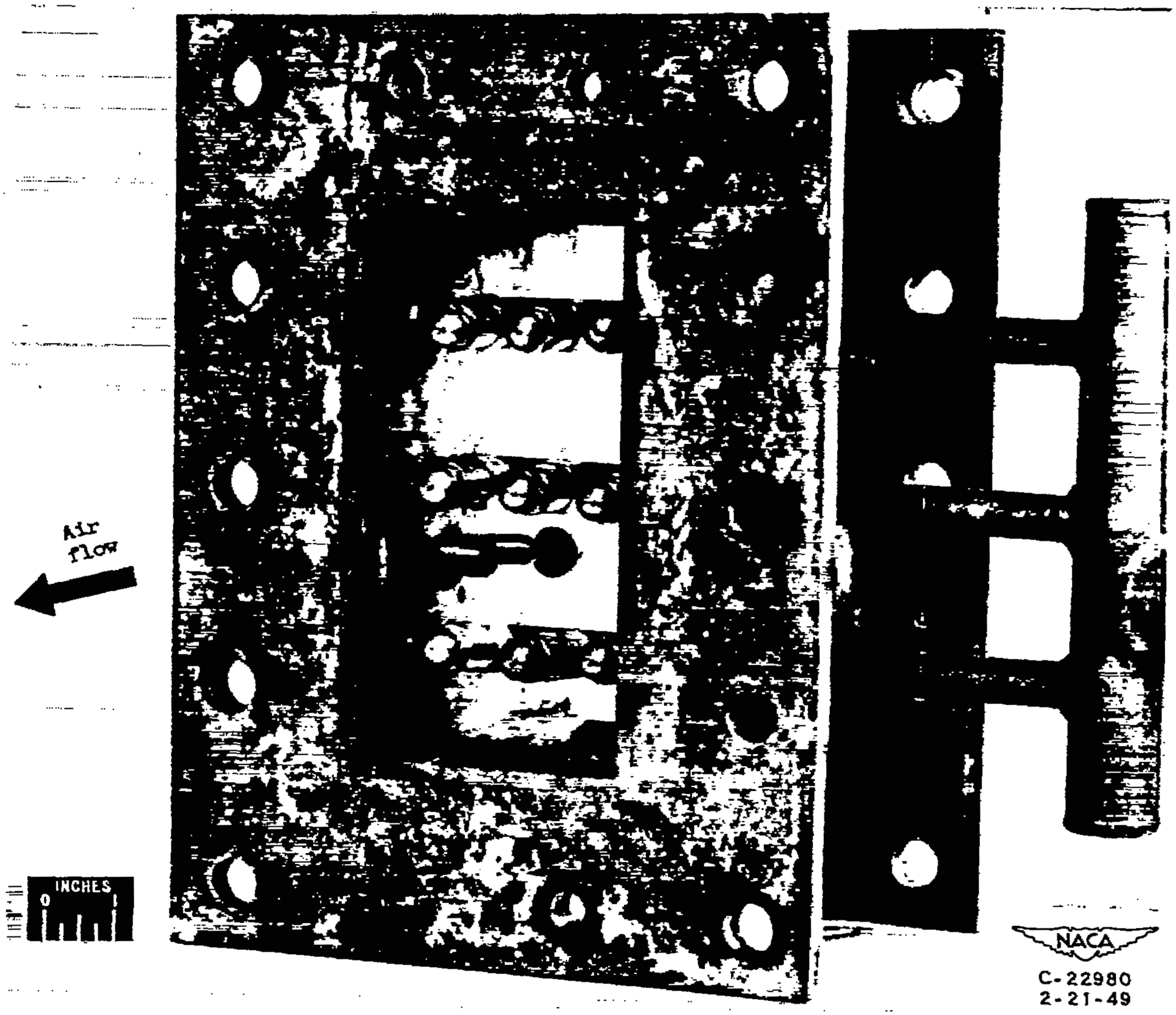
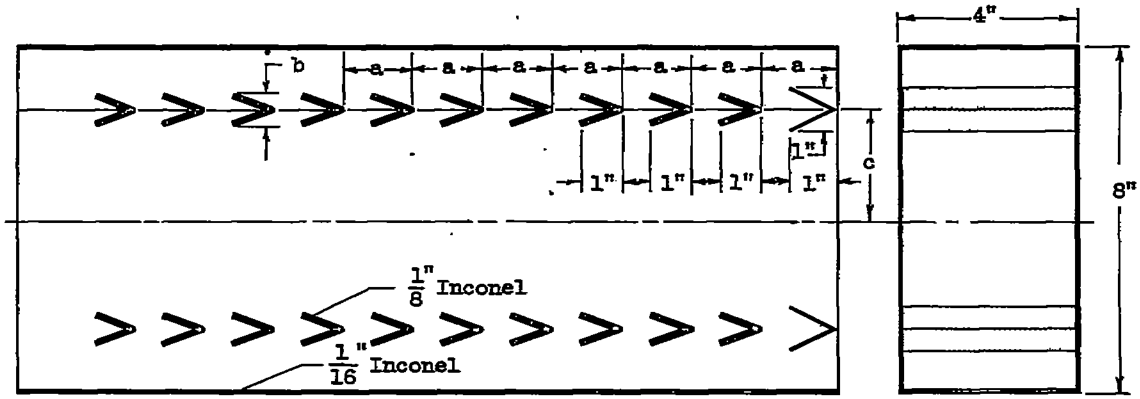


(a) Simple-orifice fuel injector.
Figure 2. - Fuel injectors for 4- by 8-inch combustor.



(b) Hollow-spray-cone fuel injector.
Figure 2. - Concluded. Fuel injectors for 4- by 8-inch combustor.



Flame-holder	Dimensions			Total gutters
	a	b	c	
1	$1\frac{1}{2}$"	$\frac{3}{4}$"	$2\frac{1}{2}$"	22
2	$2\frac{1}{2}$"	$\frac{3}{4}$"	$2\frac{1}{2}$"	14
3	$1\frac{1}{16}$"	$\frac{3}{4}$"	$2\frac{1}{2}$"	30
4	$1\frac{1}{2}$"	$\frac{3}{4}$"	2"	22
5	$1\frac{1}{2}$"	1"	$2\frac{1}{2}$"	22
6	Same as flame holder 1 except for addition of third row of gutters in center			33

Figure 3. - Schematic diagram of various gutter-type flame holders.

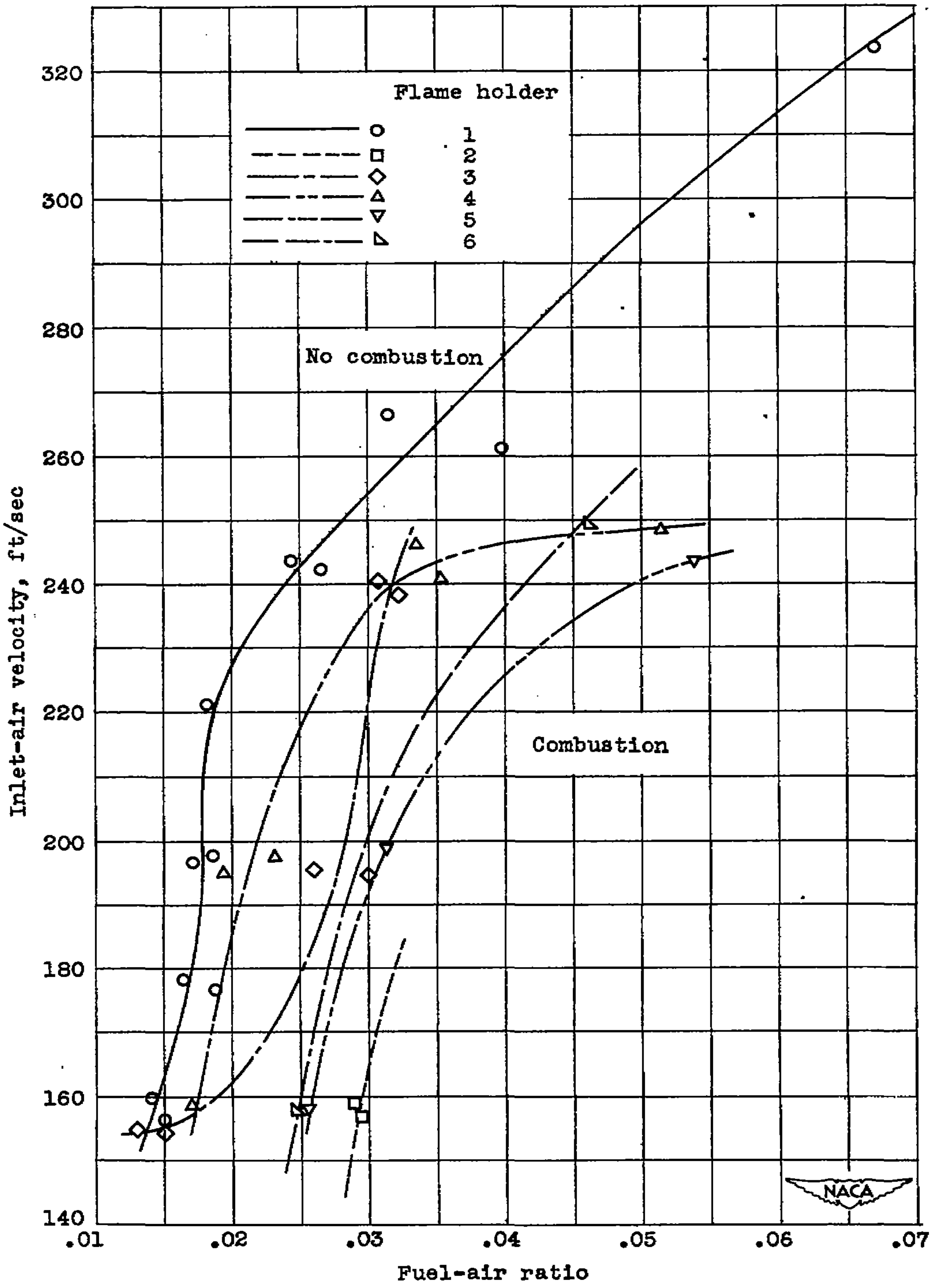


Figure 4. - Lean combustion limits for flame holders 1 to 6. Inlet-air pressure, 55 inches mercury absolute; inlet-air temperature, 200° F.

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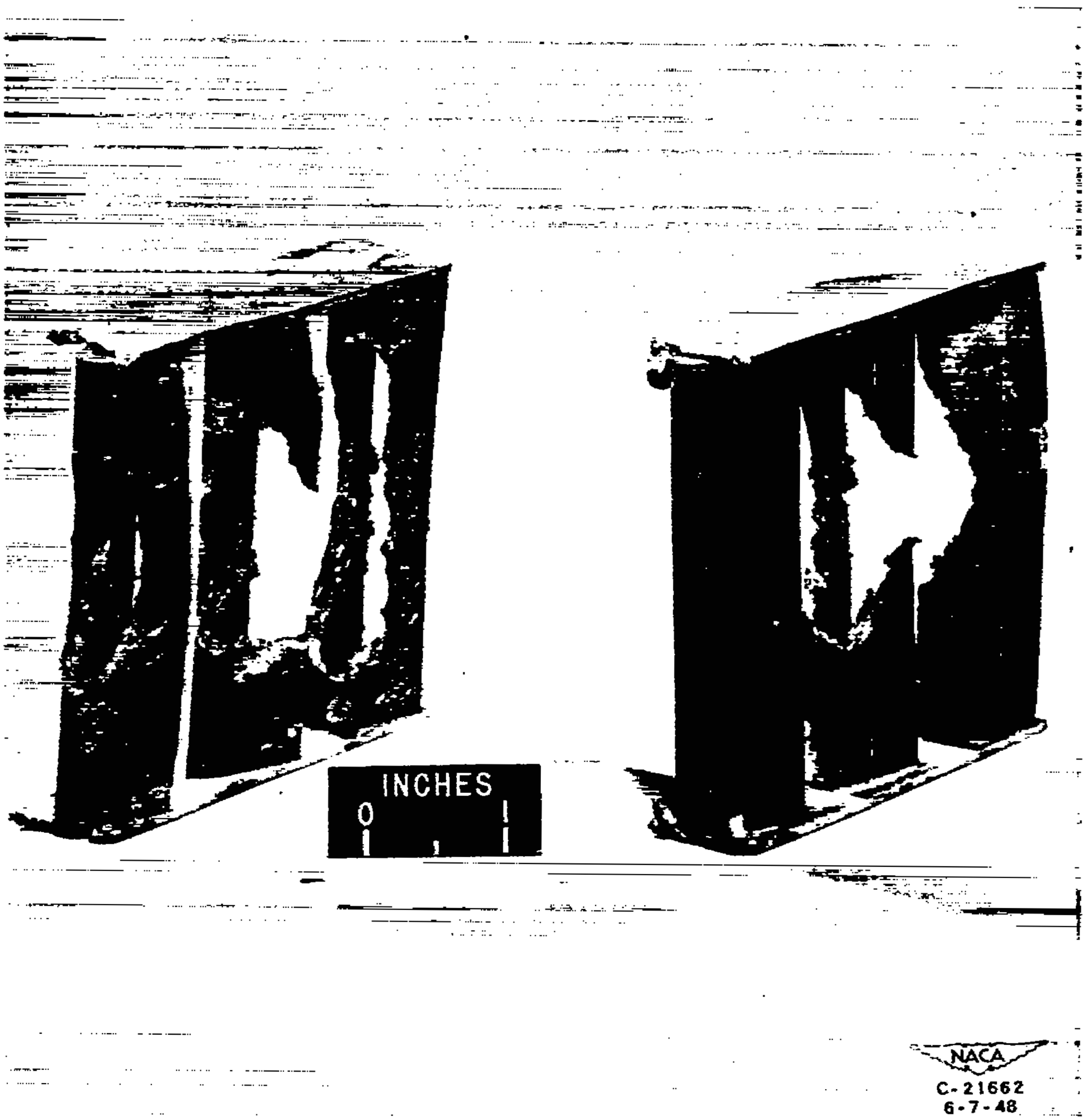

Figure 5. - Three gutters located at downstream end of two rows of flame holder 6 after 10 minutes of operation.

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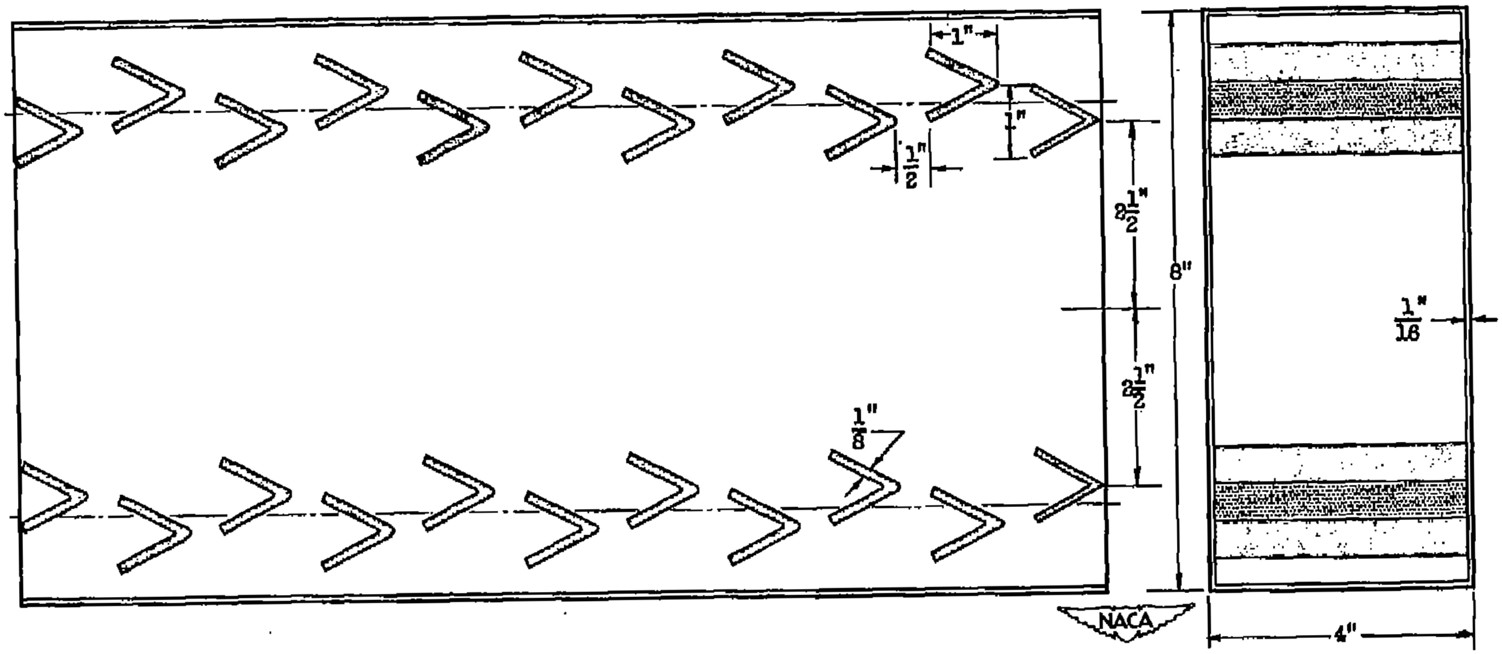

Figure 6. - Schematic diagram of flame holder 7.

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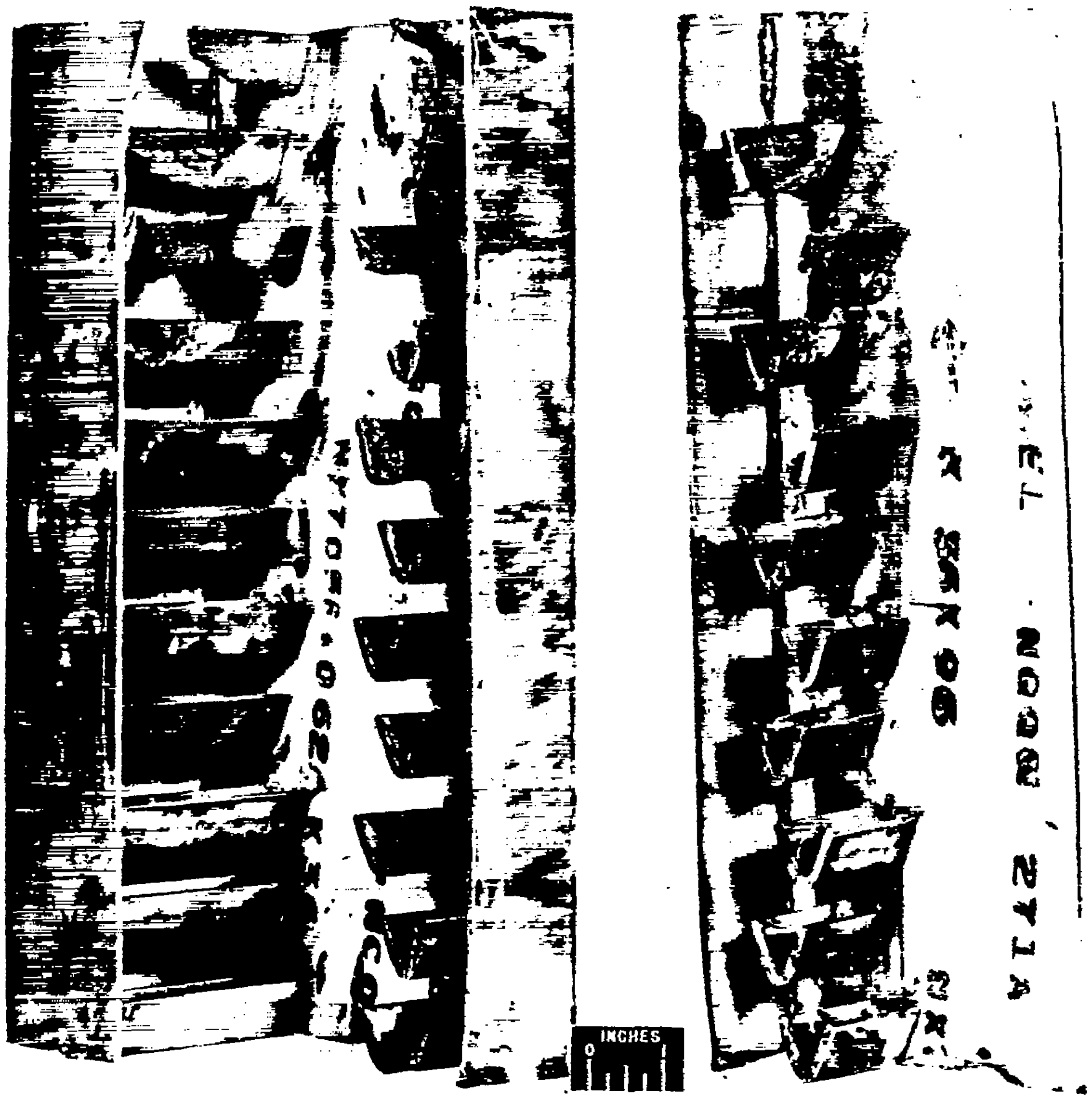

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Figure 7. Cutaway view of flame holder 7 after 10 minutes of operation.

[redacted]

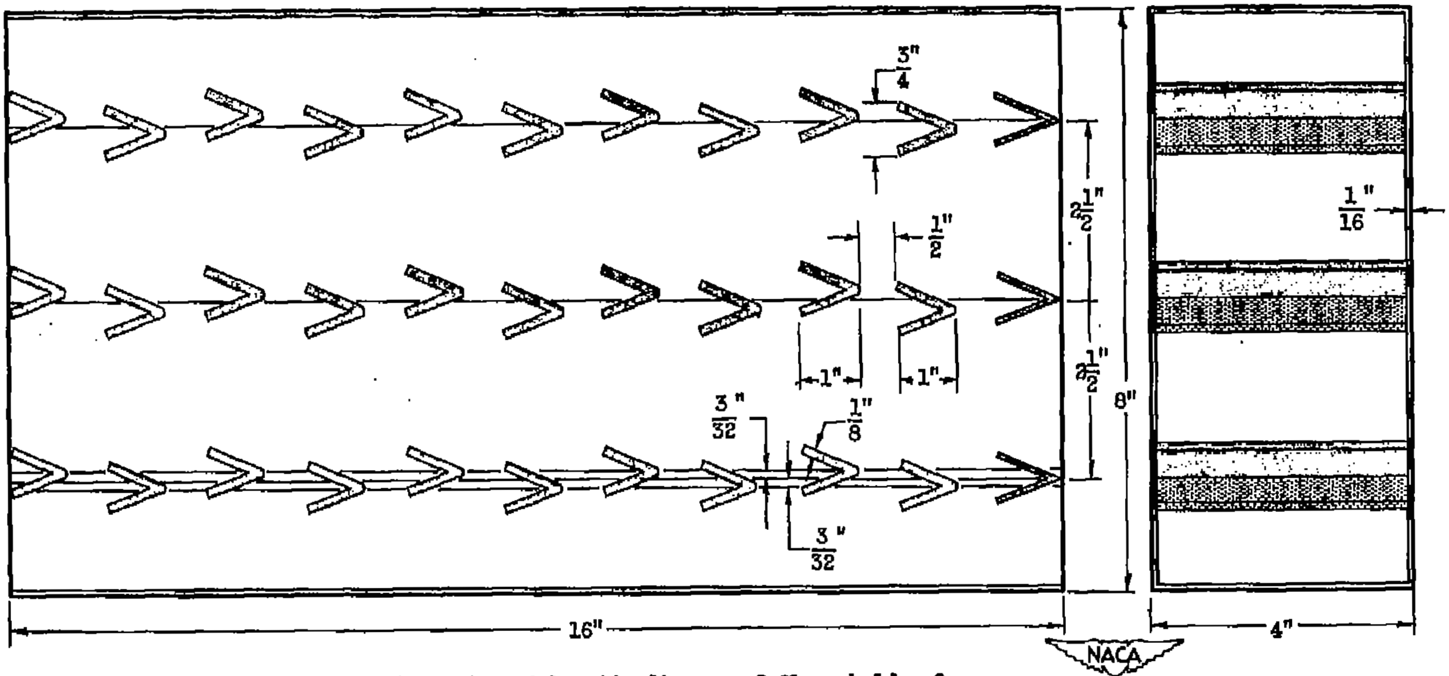

Figure 8. - Schematic diagram of flame holder 8.

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Figure 9. - Cutaway view of flame holder 8 after 10 minutes of operation.

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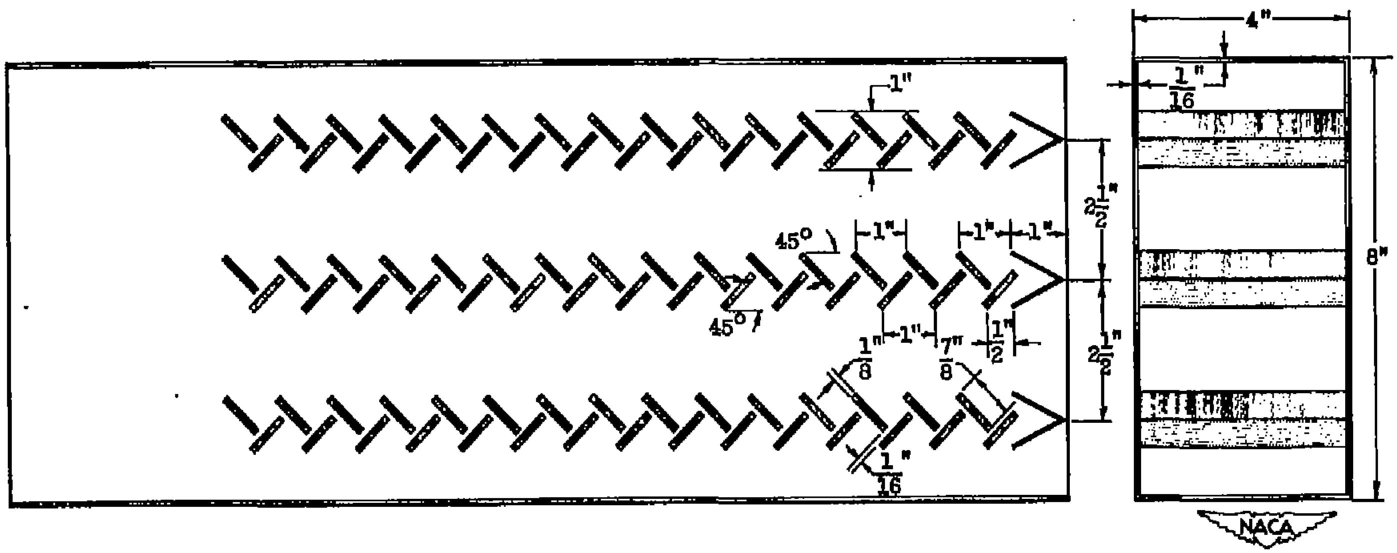

Figure 10. - Schematic diagram of flame holder 9.

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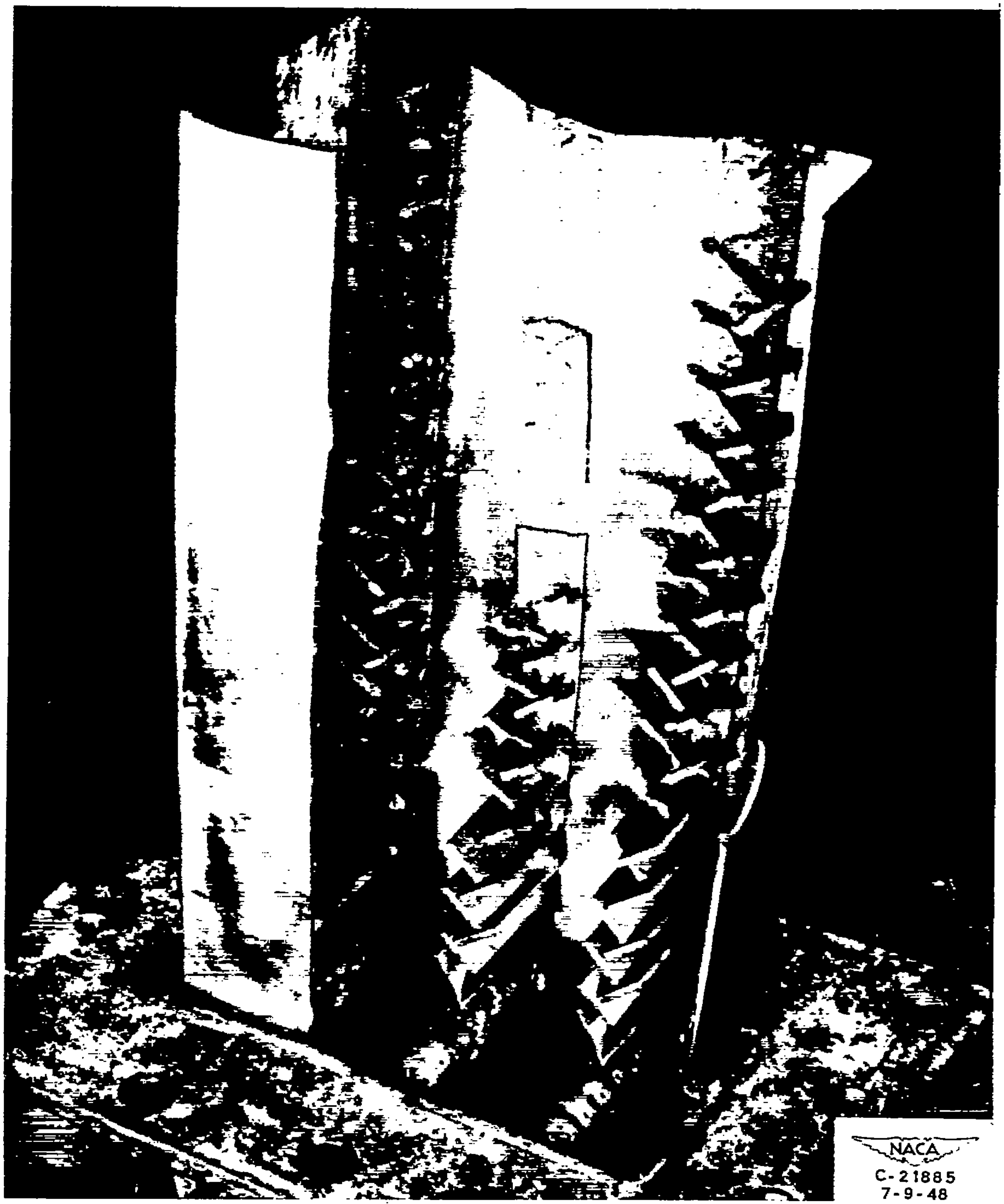

Figure 11. - Cutaway view of flame holder 9 showing position of fuel-discharge bars.

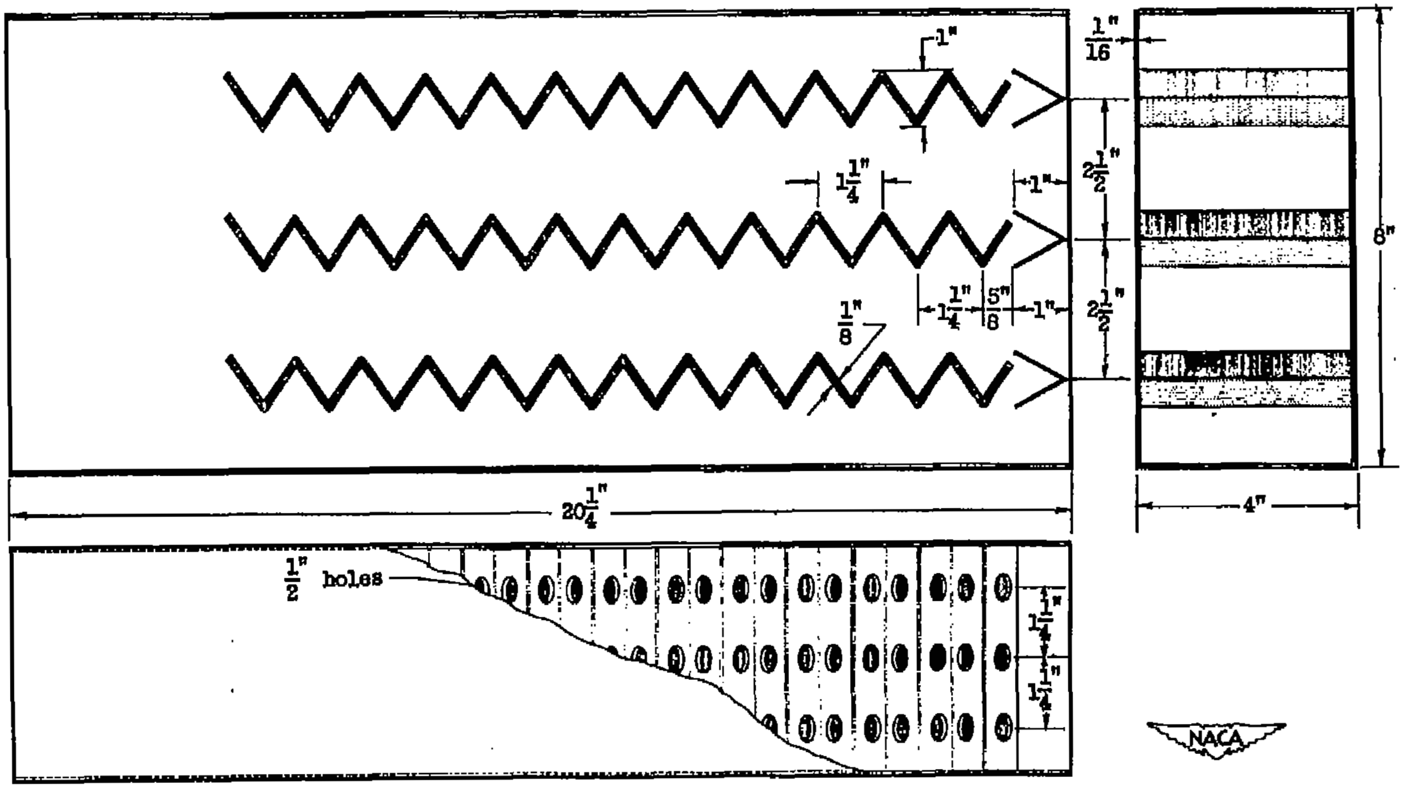

Figure 12. - Schematic diagram of flame holder 10.

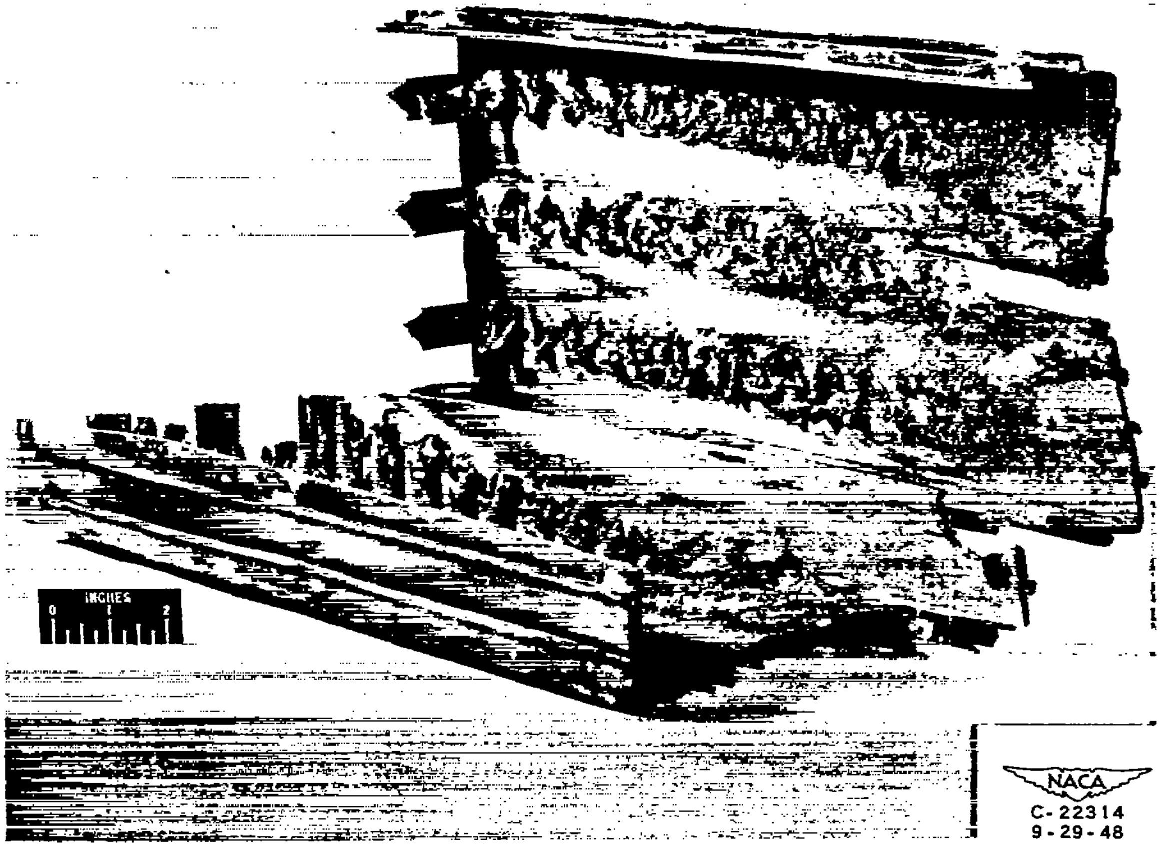

Figure 13. - Cutaway view of flame holder 10 after 5 minutes of operation.

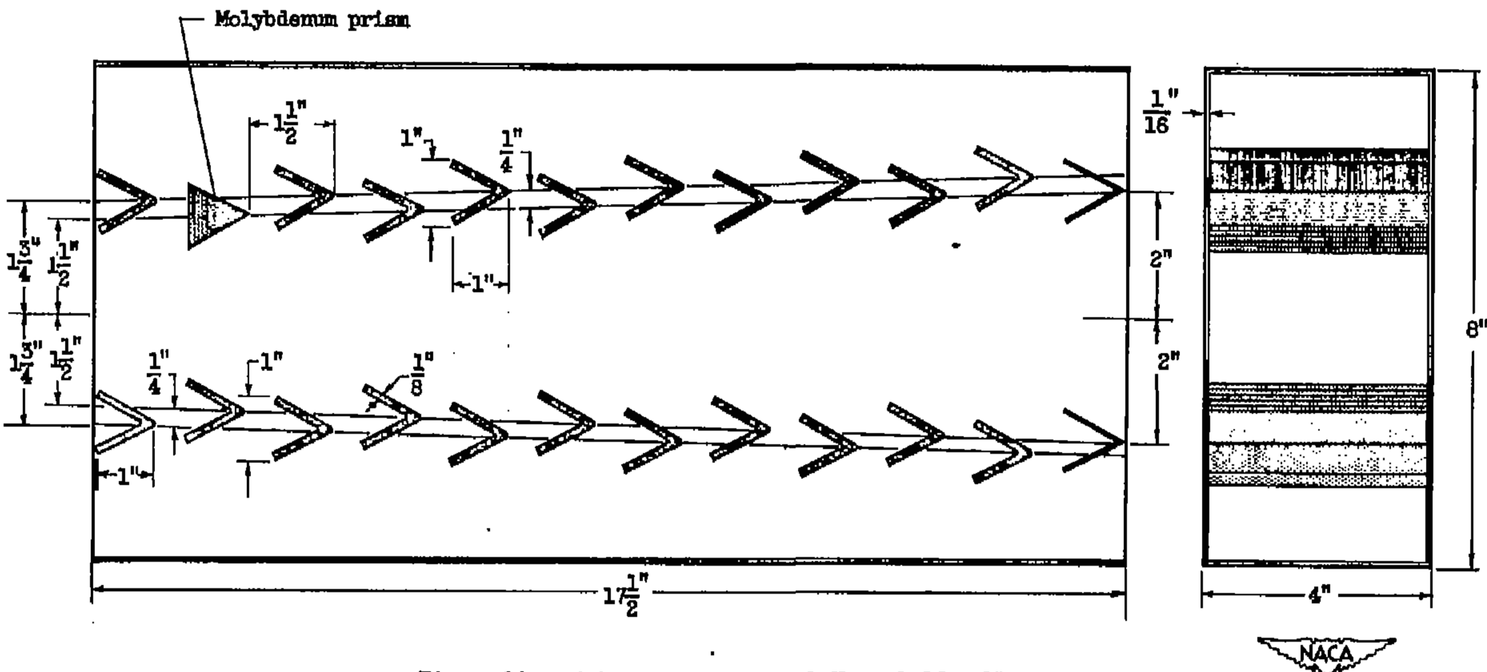

Figure 14. - Schematic diagram of flame holder 11.

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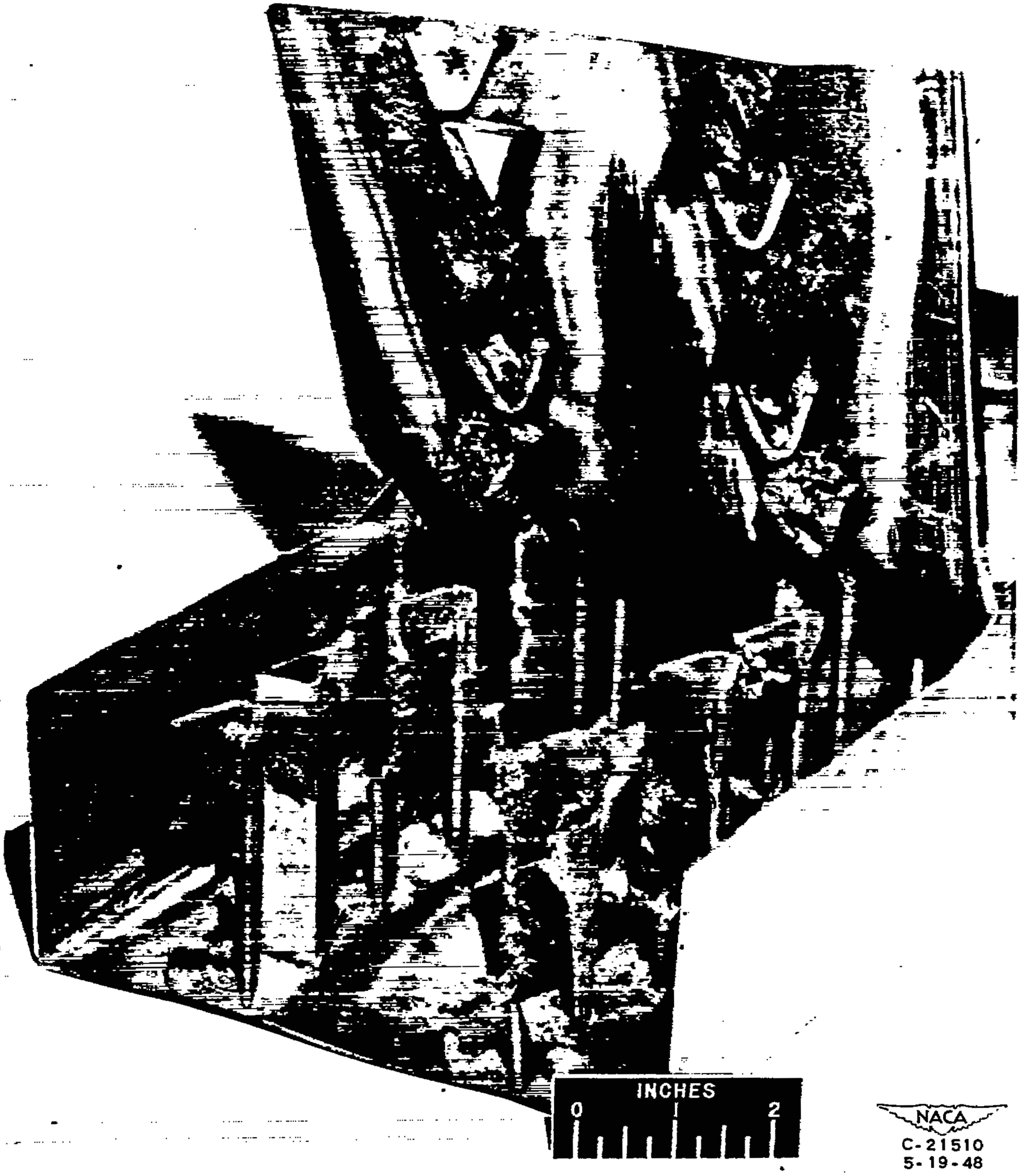

Figure 15. - Cutaway view of flame holder 11 showing condition after 5 minutes of operation. Note molybdenum prism.

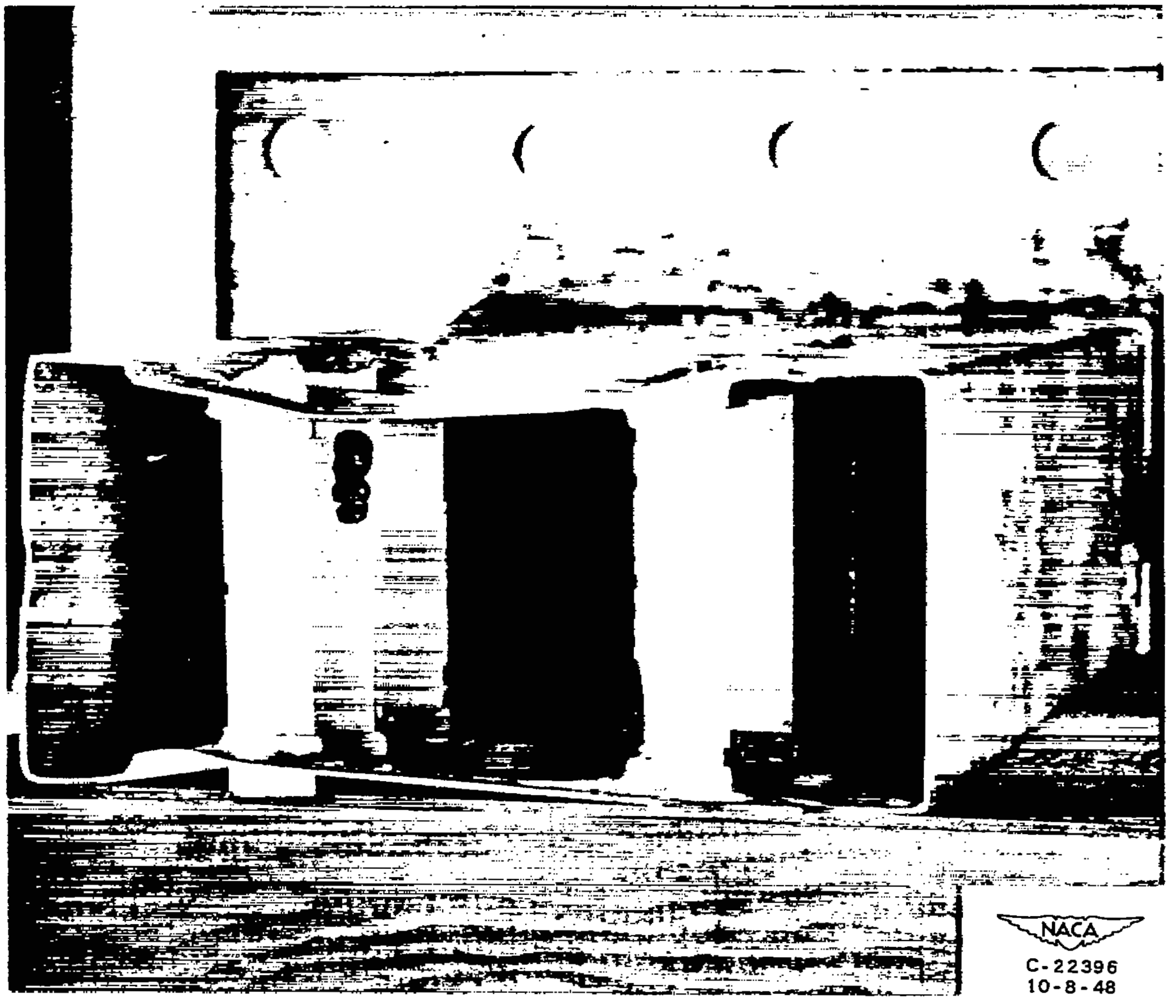

Figure 16. - Flame holder 12 after 47 minutes of operation.

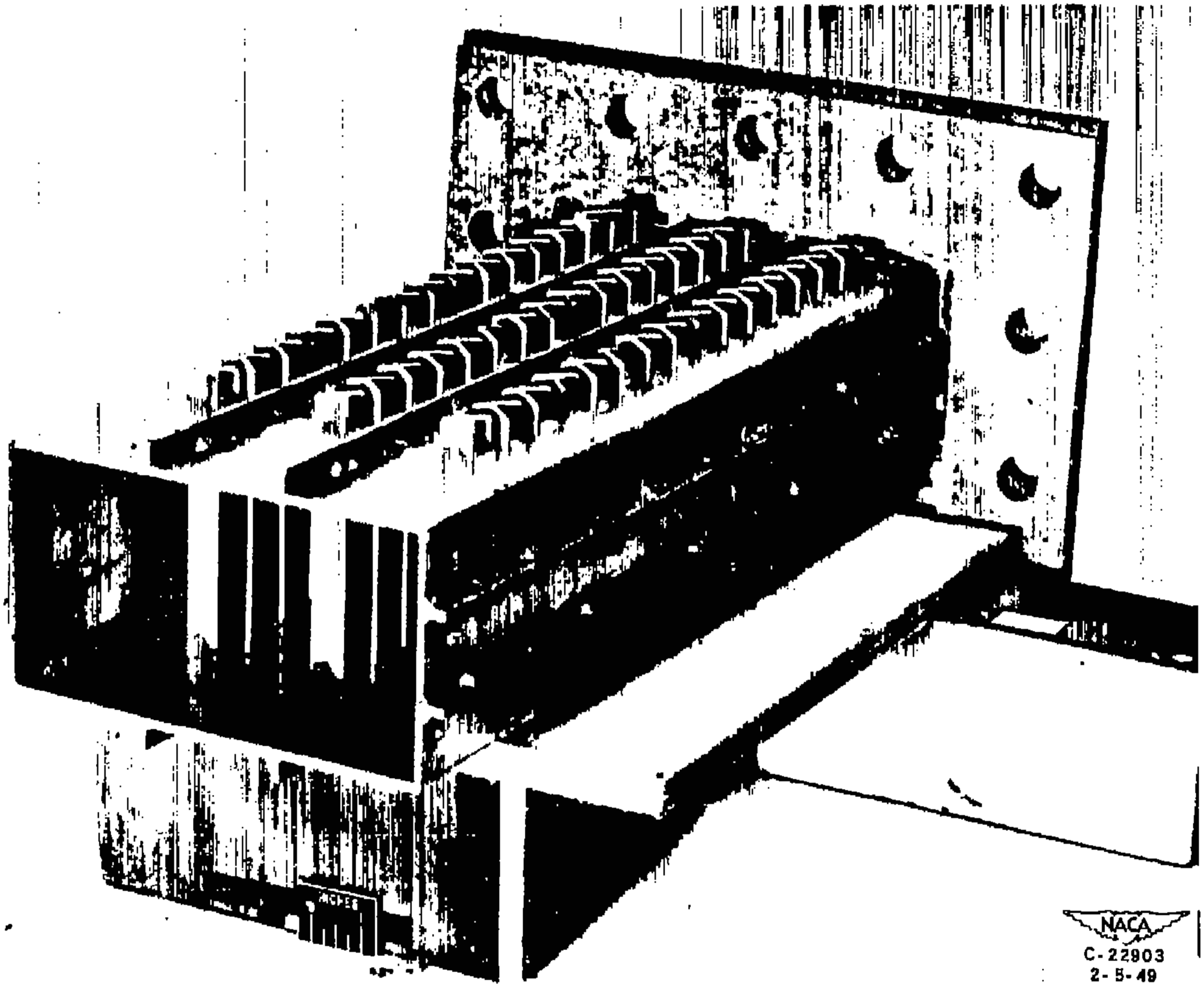

Figure 17. - Flame holder 13 showing installation of molybdenum plates before operation.

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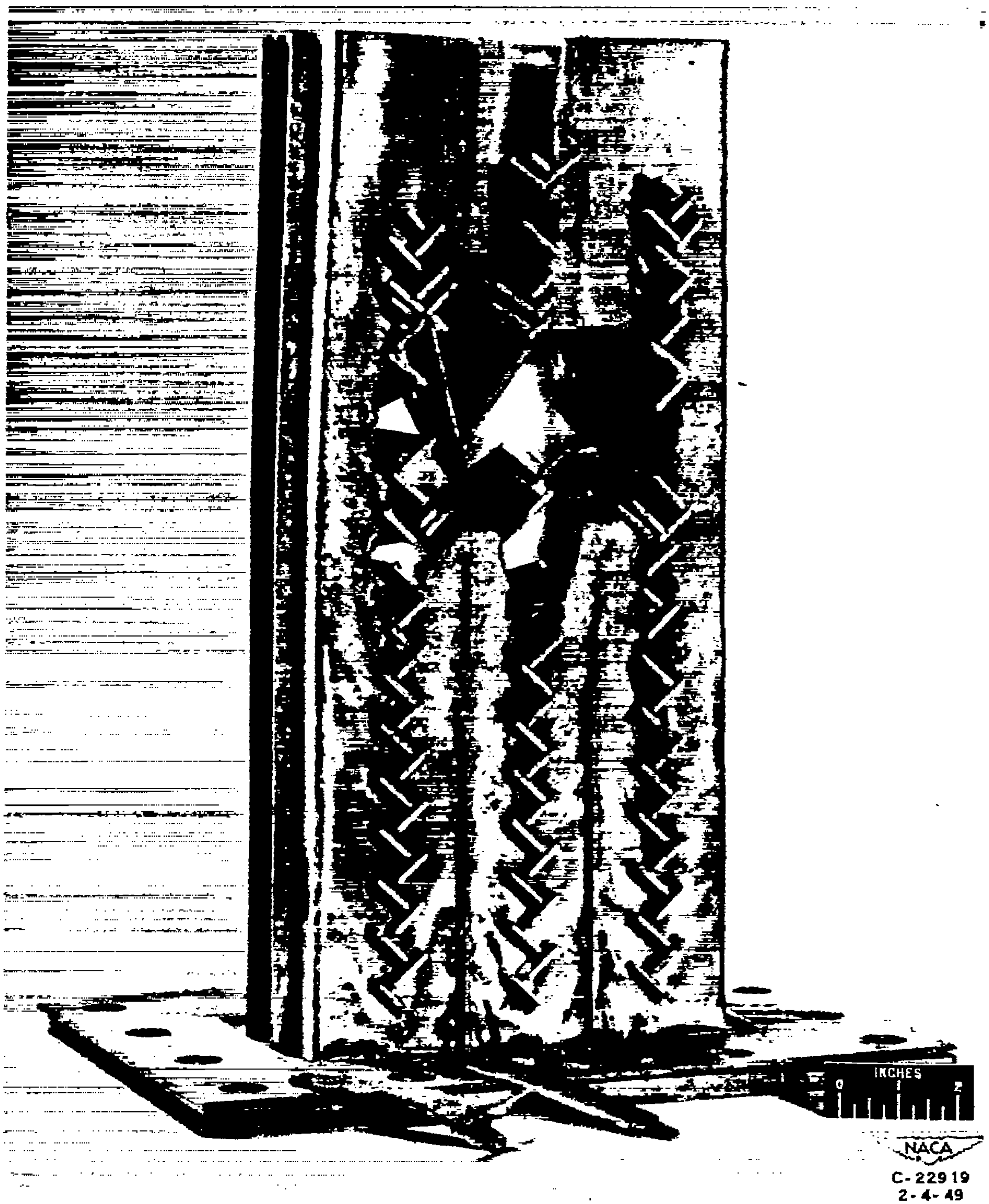
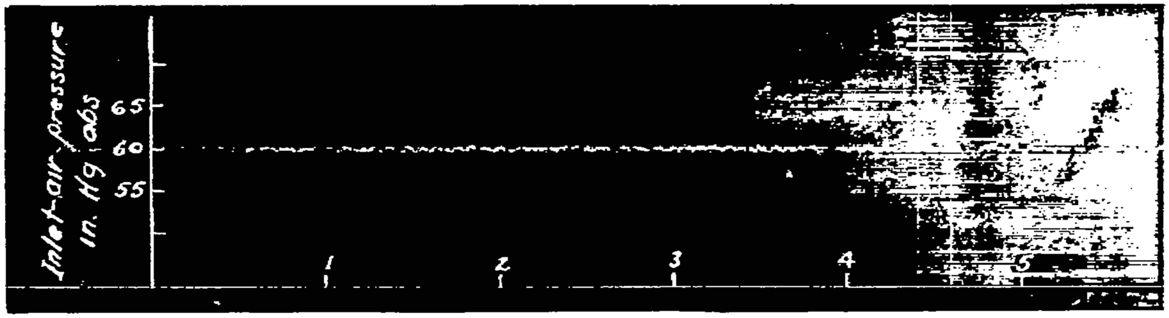


Figure 18. - Flame holder 13 after 5 minutes of operation.



Time, sec

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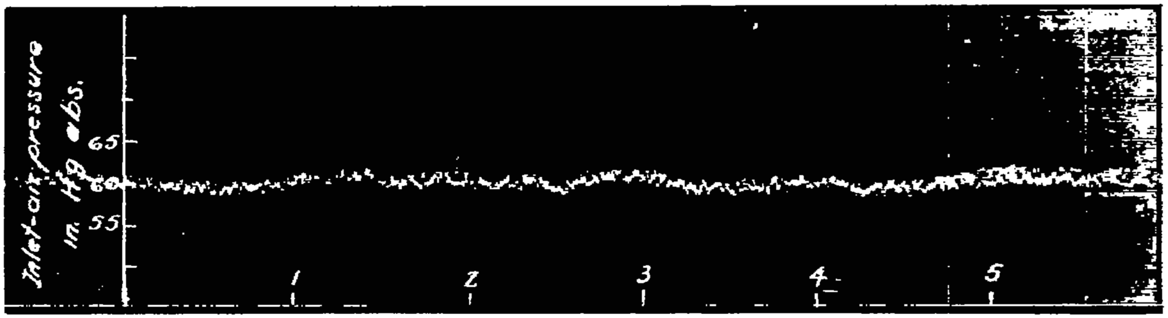
(a) No combustion



Time, sec

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(b) Combustion

Figure 19. - Pressure variation with time at 4- by 8-inch combustor inlet with flame holder 13. Inlet-air velocity, 200 feet per second; inlet-air temperature, 200° F.